Improvement of Two Operational Models for Advance Warning of Geoeffective Disturbances of Solar Origin

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LONG-TERM GOALS

To improve the prediction of traveling solar disturbances which impact the geospace environment. Such disturbances, which are associated with both coronal holes and coronal mass ejections (CMEs) launched from the Sun, can cause substantial geomagnetic effects, including the crippling of satellites, disruption of radio communications, and damage to electric power grids.

OBJECTIVES

To improve and extend the predictive capabilities of two space weather models currently in operational use at the National Oceanic and Atmospheric Administration's Space Environment Center (NOAA/SEC). The first, the Wang & Sheeley model (WS), predicts the background solar wind speed and interplanetary magnetic field (IMF) at Earth. The WS model has been improved though the incorporation of additional and more realistic physics-based models into the prediction routine. The second is the Chen model, which predicts the occurrence, strength, and duration of large non-recurrent storms due to transient events on the Sun, such as CMEs. This model's prediction routine has been modified in an effort to improve its forecast capability and reliability.

APPROACH

The Wang & Sheeley (WS) model [*Wang et al.*, 1992], a combined empirical and physics-based representation of the quasi-steady global solar wind flow, is a product of research efforts at the Naval Research Laboratory. It predicts ambient solar wind speed and IMF polarity at Earth and is thus useful for forecasting recurrent interplanetary disturbances. The NOAA/SEC implementation of the model serves two purposes with respect to space weather forecasting: 1) it provides advance warning of high-speed solar wind streams, which are associated with recurrent geomagnetic disturbances and increased high-energy electron fluences near Earth; and 2) it provides our best estimate of flow conditions and structures lying in the path of transient disturbances (such as CMEs and magnetic clouds) headed toward Earth. That is, dynamic interactions with intervening structures can have a significant impact upon the propagation speed of CMEs and can significantly influence their physical properties, such as magnetic field intensities and orientations.

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14. ABSTRACT
To improve the prediction of traveling solar disturbances which impact the geospace environment. Such disturbances, which are associated with both coronal holes and coronal mass ejections (CMEs) launched from the Sun, can cause substantial geomagnetic effects, including the crippling of satellites, disruption of radio communications, and damage to electric power grids.

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Two major modifications have been made to the WS model, which are anticipated to further improve its predictive capability and reliability. The first is the inclusion of an improved upper coronal model that spans the region from 2.5 $R_{\odot}$< R < 20-30 $R_{\odot}$. The second is the incorporation of a quick running interplanetary 3-D MHD propagation code of the solar wind (i.e., from 20-30 $R_{\odot}$< R < 1 AU). These two modifications replace the extremely crude radial propagation assumption made in the original version of the model. We have also modularized the code so as to make future improvements/modifications simpler.

The NOAA/SEC implementation of the Chen model [*Chen*, 1996 and 1997] provides real-time forecasts of the occurrence, duration, and strength of large geomagnetic storms using real-time solar wind data. The method estimates the IMF and the geoeffectiveness of the solar wind upstream of an L1 monitor such as ACE. A recently published [*Arge et al.*, 2002a] verification study on the basic version of the model has shown that it can more than double (on average) the ~1-hour advanced warning time presently available using L1 data alone. The verification study will serve as baseline to objectively measure the degree of improvement in future model upgrades.

WORK COMPLETED

Under the advisement of the PI, primary implementation responsibilities for this project have been assumed by Dr. C. N. Arge. Much of the effort spent on the Wang & Sheeley (WS) model over the last year has concentrated on two objectives: 1) enhancing the model's capabilities and sophistication, and 2) significantly improving the Wang-Sheely model web page.

As mentioned in our 2001 report, the Schatten current sheet (SCS) model [*Schatten*, 1971] has been added to the development version of the WS model to provide a more realistic magnetic field topology of the upper corona region spanning 2.5$R_{\odot}$< R < 21.5$R_{\odot}$. The output from the potential field source surface (PFSS) model, which specifies the sun's field from 1 $R_{\odot}$< R < 2.5 $R_{\odot}$, serves as the input to the SCS model. Using daily updated polar corrected photospheric field synoptic maps from Mount Wilson Solar Observatory from 1995 and the new PFSS+SCS model combination, we have found [*Arge et al.*, 2002b] a promising new empirical relationship for solar wind speed that is a function of two coronal parameters, flux tube expansion factor (f_s) and the minimum angular separation (at the photosphere) between an open field footpoint and its nearest coronal hole boundary (θ_b). The new relationship appears to work much better than one derived previously (see Figure 1), which is a function of f_s only, in that it specifies solar wind speed at the boundaries and the interiors of coronal holes much more realistically (Figure 2). We have focused on the solar wind during 1995, as we have had past difficulty successfully predicting the stream structure for this period.

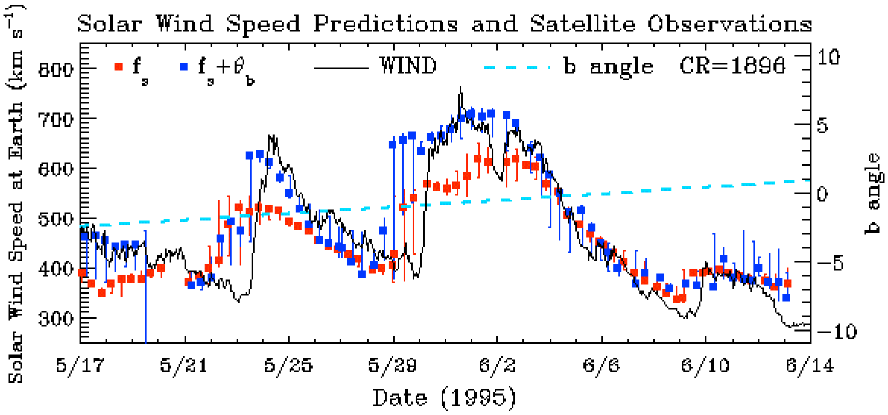

Figure 1 – Solar Wind Speed Predictions and Observations for CR 1896
[Solar wind speed observations (thin solid line) for CR 1896 and predictions (colored dots) using the PFSS+SCS model combination and the old (red squares) and new (blue squares) empirical solar wind speed relationships. The vertical bars are uncertainty estimates determined by calculating the solar wind speeds for values located 2.5° above and below the sub-earth points.]

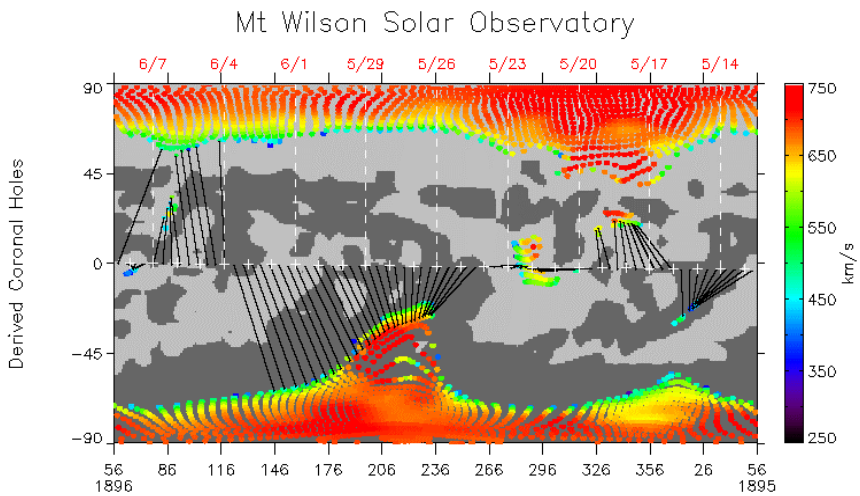

Figure 2. Derived Coronal Holes for CR1896 and Photospheric Field Polarity
[Light (dark) gray corresponds to positive (negative) polarity. Solar wind speed (i.e., indicated by dot color) assigned using the new empirical relationship mentioned in the text. The white crosses mark the daily positions of the sub-earth point. The black straight lines identify the connectivity between the outer boundary and the source regions of the solar wind at the photosphere.]

Over the last year, we conducted a number of test runs in which the output from the PFSS+SCS model combination (i.e., such as that shown in Figure 2) has been used as input to a numerical 3-D MHD solar wind propagation code. Two different MHD solar wind codes, Han-Detman [*Detman et al.*, 1991] and Odstrcil [*Odstrcil and Pizzo*, 1999a,b], have been tested in this manner. Figure 3 shows simulation results for Carrington rotations (CR) 1891-1894 using the Odstrcil MHD model. Similar results have been obtained using the Han-Detman MHD code. However, the latter code has trouble satisfying the divergence free requirement when daily-updated maps (as opposed to full Carrington synoptic maps) are used. This problem has not appeared in Odstrcil's more advanced MHD model.

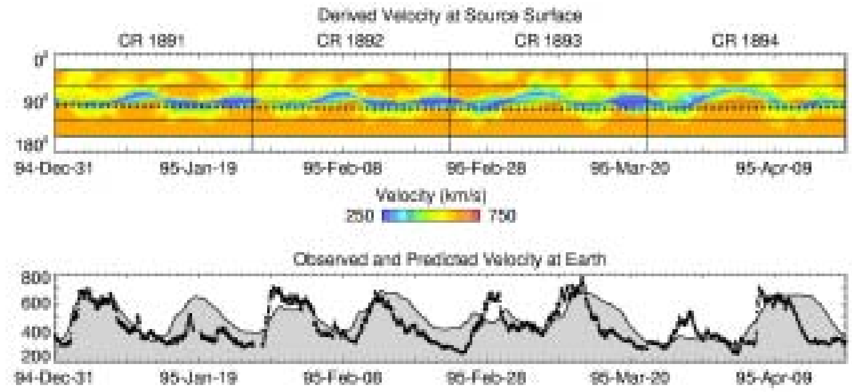

Figure 3. Solar Wind Speed Predictions at 21.5 $R_{\odot}$ and 1 AU
[(Top) Solar Wind Speed at 21.5 $R_{\odot}$, as specified by the empirical WS relationship, for Carrington rotations CR 1891-1894. The black dots near the equator mark the daily positions of the sub-earth point. (Bottom) Comparison of solar wind speed observations (block dots) with predictions (filled gray curve) using the Odstrcil numerical MHD solar wind propagation code.]

Our experience with the Han-Detman code has led us to conclude that it would be highly desirable to replace it with one that is more sophisticated, but at the same time, substantially less demanding of resources than the Odstrcil model. The Zeus-3d [*Stone and Norman*, 1992a,b] numerical MHD code is a very promising candidate.

In Fall 2001, we began a collaboration with Lance Williams at TRW who was, at the time, developing a generalized Java-based modular control routine. The collaboration was mutually beneficial, for Williams' Java routine appeared ideally suited to (eventually) replace the main control software currently used with the WS model. However, he lacked access to a set of simple operational models to work with, which we were able to provide. We worked with Williams on this mutual effort through April 2002 when he provided us with the final version of his control software. We continue to improve and modify his code and intend to use it as the primary control code for WS.

Last year we significantly improved the NOAA/SEC operational Wang-Sheeley web page with the assistance of programmer Leslie Mayer. The web page's structure is now more logical and much easier to use. Further improvements will be added very soon, such as daily-updated 2-dimensional (2-D) plots (i.e., in the ecliptic plane) of solar wind speed and IMF polarity such as shown in Figure 4 below. A development page (not yet accessible to outside users) already includes these plots. These new maps will provide forecasters with a 2-D view of the solar wind in the ecliptic plane and therefore knowledge of the structures lying between the Sun and Earth.

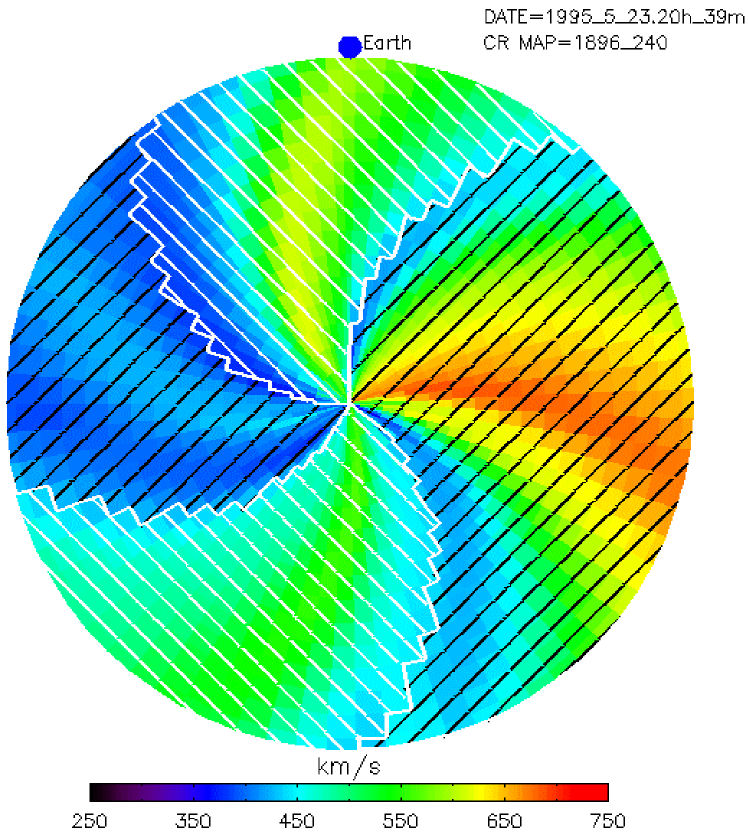

Figure 4. 2-D Solar Wind Speed and IMF Polarity in the Plane of the Ecliptic [Bright red corresponds to high (~750 km s^{-1}) while dark blue to slow (~250 km s^{-1}) solar wind speed. Regions filled with white (black) diagonal lines have magnetic field lines directed radially outward (inward) from (toward) the Sun. The Sun is located at the center of the plot while Earth is positioned near top-center.]

The NOAA/SEC implementation of the Chen model makes hourly forecasts of the likelihood of imminent approach of large geomagnetic storm producing solar wind using a near-real-time data link from the Advanced Composition Explorer (ACE) satellite in an L1 orbit. The real-time predictions are made available and current to the SEC forecasters and the broader research community via the Chen Model web page listed above.

Last year we reported the results of a three-year verification study using the very reliable Level 2 ACE data. The results of the study showed that the model performs very well. It successfully predicted ~80% actual events, and it provided an average warning time of 2.1±2.5 hours. A journal paper summarizing these results has been accepted for publication and is expected to appear in print soon [*Arge et al.*, 2002a]. We are in the process of extending this verification study to a four-year time interval and plan to write a more comprehensive journal paper on the model's performance.

Given the very encouraging prediction performance of the Chen model, it was appropriate to improve its web page, which was very basic and provided little guidance to the unfamiliar user. The web page was completely redesigned with key predictions summarized on the first page in a compact, but easy-

to-understand format. Links were added that provide users with a detailed explanation (with examples) of the model as well access to the above mentioned verification study. Significant effort was spent on redesigning the automated control script so that it is both very robust and capable of restarting or resuming the model without manual intervention, should data used by it be unavailable for an extended period of time. The model now includes real-time *Dst* predictions to compare with the Chen model predictions (http://sprg.ssl.berkeley.edu/dst_index/). Last May, SEC forecasters were presented with the results of our 3-year verification study on the model, along with the redesigned Chen web page.

RESULTS

The incorporation of more sophisticated physical models within the WS model framework is very likely to improve measurably forecasts of the background solar wind, as evidenced by our discovery of the improved empirical relationship for solar wind speed. Modularization of the WS prediction routine will permit easy replacement of individual models by improved models as they (and any required data streams) become available. Incorporation of Williams' generalized Java-based modular control routine will be very helpful in this effort. In addition to direct operational use at NOAA/SEC and other forecast centers, the WS model has been enjoying increasing interest and application in the areas of space weather and solar-interplanetary research as well as educational outreach. A clear indication of both the success and acceptance of the WS model in the space weather and solar-interplanetary research community is the recent decision by the National Science Foundation's newly instituted Center for Integrated Space Weather Modeling (CISM) to utilize it as part of their empirical modeling effort. For a second year in a row, Dr. Arge was invited to teach both a lab and lecture at Boston University's two-week Space Weather CISM Summer School. The Chen model is showing real promise as a practical forecasting tool and continues to provide warnings of geomagnetic storms often (many) hours in advance of their onset. We believe the new NOAA/SEC Chen model web page will help make the model easier to understand and use.

IMPACT/APPLICATIONS

Eventually, a highly verified and robust modular version of the WS will replace the operational WS model presently used at NOAA/SEC. As improved models, predictions, and graphics emerge from the development of this model they will augment or replace those presently found on the NOAA/SEC Wang & Sheeley web site listed above. The results of the recent validation study of the Chen model are very encouraging.

TRANSITIONS

NOAA/SEC forecasters are using these tools as does the space weather research community. Next year the WS model will be incorporated into the CISM empirical modeling effort. The Community Coordinated Modeling Center (CCMC) has recently expressed interest in acquiring the WS model.

RELATED PROJECTS

Dr. Arge will participate in the recently funded CISM project. He will be working closely with researchers at the High Altitude Observatory (HAO) and has the role of liaison scientist between the solar CISM effort and HAO. Dr. Arge will be serving on the CCMC's Scientific Working Group for the next two years.

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